TOPEX/Poseidon and Jason-1: Absolute Calibration in Bass Strait, Australia

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Updated absolute calibration results from Bass Strait, Australia, are presented for the TOPEX/Poseidon (T/P) and Jason-1 altimeter missions. Data from an oceanographic mooring array and coastal tide gauge have been used in addition to the previously described episodic GPS buoy deployments. The results represent a significant improvement in absolute bias estimates for the Bass Strait site. The extended methodology has allowed comparison between the altimeter and in situ data on a cycle-by-cycle basis over the duration of the dedicated calibration phase (formation flight period) of the Jason-1 mission. In addition, it has allowed absolute bias results to be extended to include all cycles since the T/P launch, and all Jason-1 data up to cycle 60. Updated estimates and formal 1-sigma uncertainties of the absolute bias computed throughout the formation flight period are $0 \pm 14 \text{ mm}$ for T/P and $+152 \pm 13 \text{ mm}$ for Jason-1 (for the GDR POE orbits). When JPL GPS orbits are used for cycles 1 to 60, the Jason-1 bias estimate is 131 mm, virtually identical to the NASA estimate from the Harvest Platform off California calculated with the GPS orbits and not significantly different to the CNES estimate from Corsica. The inference of geographically correlated errors in the GDR POE orbits (estimated to be approximately 17 mm at Bass Strait) highlights the importance of maintaining globally distributed verification sites and makes it clear that further work is required to improve our understanding of the Jason-1 instrument and algorithm behavior.

**Keywords** altimeter calibration, GPS buoy, Jason-1, TOPEX/Poseidon

The Jason-1 satellite altimeter was launched in December 2001 by mission partners United States National Aeronautics and Space Administration (NASA) and the French Space Agency, Centre National d’Etudes Spatiales (CNES). The Jason-1 satellite represents a follow-on mission to the exceptionally successful TOPEX/Poseidon (T/P) spacecraft which is still operating a decade after its launch in August 1992. During the calibration and verification phase of the Jason-1 mission, the spacecraft was placed in an orbit which achieved identical ground tracks to T/P, slightly leading the T/P spacecraft by approximately 1 minute and 10 seconds. This configuration (the formation flight phase) lasted for approximately seven months, allowing for the cross calibration of instruments on board the Jason-1 spacecraft. This strategy was designed to ensure the consistency of the long-term sea-level record as derived from the satellite altimeters (see Ménard and Haines 2001). Accurate calibration is essential for many studies, especially studies of global and regional sea-level change. An understanding of the overall system accuracy and stability is therefore of considerable importance. For this reason, the NASA and CNES agencies have operated dedicated in situ calibration sites at both Harvest (Haines et al. 2003) and Corsica (Bonnefond et al. 2003) respectively.

The Bass Strait calibration site provides an important contribution to the global calibration of both T/P and Jason-1. The Bass Strait site is the only calibration site in the Southern Hemisphere and unlike the Harvest and Corsica sites, is located on a descending altimeter
The first study undertaken at the site followed the launch of the T/P altimeter in 1992 (see White et al. 1994). This initial study relied on tide-gauge data augmented with a marine geoid computed from local gravity and altimeter data to derive estimates of absolute bias for T/P following its launch. More recently following the launch of Jason-1, the Bass Strait site has been revisited utilizing an updated and enhanced calibration methodology. To remove the uncertainty associated with estimating a marine geoid, Watson et al. (2003) used a purely geometric approach and demonstrated the value of the Bass Strait site by providing independent estimates of altimeter absolute bias, computed using a different methodology and processing strategy to other dedicated calibration teams.

Bass Strait itself separates Tasmania from the Australian mainland, with the calibration site located on the south west side, near the city of Burnie (Figure 1). Bass Strait is a shallow body of water with typical depths between 60 and 80 m (51 m at the calibration site). Tidal currents near the calibration site are typically around 10–20 cms$^{-1}$, and nontidal currents mostly around 5–10 cms$^{-1}$. Also at the calibration site, observational data show that the water column is stratified during the austral summer, and well mixed from February onwards.

Initial analysis for this project focused on developing the GPS buoy system and the determination of absolute bias using solely GPS buoy deployments (Watson et al. 2003). Subsequently, following the retrieval of the oceanographic mooring array from the calibration site, analysis has progressed to incorporating mooring and tide-gauge data, allowing comparison with the altimeter on a cycle-by-cycle basis. The mooring array provides a highly precise sea surface height (SSH) time series, corrected for density changes in the water column. This refined methodology relies on using GPS buoy deployments to solve for the arbitrary datum of the mooring SSH time series. The Burnie tide gauge is also utilized to extend the analysis beyond the period the mooring was deployed (i.e., beyond

![FIGURE 1 Bass Strait Calibration Site. Land based GPS sites (BUR1, TBCP and RKCP) are shown with a triangle symbol. Inshore, central and offshore (comparison point) mooring sites are shown along the altimeter ground track using ‘+’ symbols.](image)
the TOPEX/Poseidon, Jason-1 formation flight phase). Tidal analysis of the differences between the tide gauge and mooring time series are used to compute a correction time series, effectively transforming the tide gauge observations offshore to the comparison point.

**Calibration Methodology**

The enhanced calibration methodology at the Bass Strait calibration site is focused on the determination of sea surface height (SSH) at the chosen comparison point, using data from three separate instrument ensembles. Estimates of absolute bias (Bias\(_{\text{Alt}}\)) can be derived according to the simple relation given by Watson et al. (2003):

\[
\text{Bias}_{\text{Alt}} = \text{SSH}_{\text{Alt}} - \text{SSH}_{\text{Comparison Point}},
\]

where \(\text{SSH}_{\text{Alt}}\) is determined using the altimeter, and \(\text{SSH}_{\text{Comparison Point}}\) is an estimate derived using in situ instrumentation and with reference to the land, both determined at the comparison point location in the same coordinate reference system. The reference system used by the altimeter is defined by the orbit computation technique. To ensure an equivalent reference frame for the terrestrial estimate, \(\text{SSH}_{\text{Comparison Point}}\) is determined relative to a regional GPS network, constrained to ITRF2000 coordinate estimates (Altamimi et al. 2002).

Over the time taken to observe a regional GPS network (typically many individual 24-h solutions are combined) the crust behaves elastically in response to the lunisolar potential and various mass loadings (ocean and atmosphere for example). For this reason, corrections are made for each GPS observation in the GPS analysis, such that the final position and height estimates are derived using ITRF2000, expressed relative to an ellipsoid, but in relation to a nontidal, rigid crust (i.e., the effect of the lunisolar attraction and loading signals are removed using available models). The datum used to define \(\text{SSH}_{\text{Comparison Point}}\) estimates therefore relate to a noninstantaneous, nontidal crust. This is in contrast to \(\text{SSH}_{\text{Alt}}\) where measurements relate to the instantaneous position of the crust and ocean (relative to the fixed surface of the ellipsoid), and hence for comparison require correction to refer to the nontidal crustal position. With reference to Figure 2, the corrected sea surface height derived from the altimeter is defined in Equation 2:

\[
\text{SSH}_{\text{Alt}} = h_{\text{Alt}} - (r_{\text{Alt}} + r_{\text{Corr}}) + \text{CTGG}_{\text{Corr}} + \text{TL}_{\text{Corr}},
\]

where \(h_{\text{Alt}}\) is the height of the altimeter above the reference ellipsoid, \(r_{\text{Alt}}\) is the observed altimeter range to the instantaneous sea surface, \(r_{\text{Corr}}\) is the sum of the associated path length and surface corrections, CTGG\(_{\text{Corr}}\) is a correction to account for the cross-track geoid gradient between the altimeter ground track and the position of the comparison point and TL\(_{\text{Corr}}\) are corrections needed to reduce the SSH estimate to the nontidal crust, making them consistent with \(\text{SSH}_{\text{Comparison Point}}\).

The primary in situ measurement at the comparison point is a SSH value determined on an episodic basis using GPS buoys (\(\text{SSH}_{\text{Buoy}}\)), as defined in Equation 3.

\[
\text{SSH}_{\text{Buoy}} = h_{\text{Buoy}} = h_{\text{RefGPS}} + dh_{\text{RefGPS to Buoy}},
\]

where \(h_{\text{Buoy}}\) is the height of the buoy (reduced to mean water level) above the reference ellipsoid. This measurement is derived relative to positions of GPS reference stations (\(h_{\text{RefGPS}}\)) using the estimated change in ellipsoidal height to the buoy (\(dh_{\text{RefGPS to Buoy}}\)). As discussed
FIGURE 2 Revised calibration geometry at the Bass Strait calibration site. The GPS buoy sea surface heights are used to define the datum of the mooring array and the corrected tide gauge sea surface heights.

previously, the methodology and length of data required to compute $h_{Ref\,GPS}$ dictates that final estimates of $SSH_{Buoy}$ relate to the nontidal datum.

Also at the comparison point, an offshore mooring array is utilized to estimate water height ($d_{Mooring}$), relative to the pressure sensor anchored to the sea floor. The calculation of the $d_{Mooring}$ time series from the offshore mooring array is discussed in a later section of this paper. The mooring data alone refer to an arbitrary datum and are hence not directly comparable to $SSH_{Alt}$. The absolute datum of the mooring data is defined using estimates of absolute SSH determined from the GPS buoys ($SSH_{Buoy}$). This technique involves direct comparison of the $d_{Mooring}$ series with data from the GPS buoys. The datum solution enables the calculation of $SSH_{Mooring}$, which is directly comparable with SSH estimates measured by the altimeters (Equation 4).

$$SSH_{Mooring} = d_{Mooring} + \text{mean}(SSH_{Buoy} - d_{Mooring}).$$

Note that the mooring is considered fixed to the sea floor which is subject to the same elastic response to variations in gravitational potential and mass loading. No correction is however required to the mooring time series as the deformations are assumed identical at the ocean surface (i.e., the $d_{Mooring}$ time series does not include a geophysical or mass loading component). The $SSH_{Mooring}$ and $SSH_{Buoy}$ time series can therefore be directly compared and are relative to the noninstantaneous, nontidal crustal position, expressed relative to the reference ellipsoid). Throughout its deployment the mooring array provides continuous measurement allowing comparison with the altimeter on a cycle-by-cycle basis.

A third instrument operated at the Bass Strait calibration site is an acoustic tide gauge, located at Burnie approximately 40 km from the offshore comparison point (see Figure 1). The tide gauge measures ranges to the sea surface ($r_{TG}$) relative to the tide gauge zero. The tide gauge data allow the extended cycle-by-cycle comparison with the altimeter both before and after the mooring deployment.

The use of a tide gauge located away from the altimeter comparison point complicates the determination of absolute bias. The sea surface height measured by the tide gauge
will differ from sea level at the comparison point due to a range of influences including oceanographic conditions (tidal differences, along and cross-shore currents), meteorological differences (wind setup, atmospheric pressure differences), geophysical differences (differential tidal and nontidal loading) and geometric differences (geoid/ellipsoid slope). The methodology adopted to overcome these differences relies on both the SSHMooring and the SSHBuoy time series. In the most simplified form, the tide gauge data \( r_{TG} \) are transformed to absolute sea surface heights at the comparison point using the relation:

\[
SSH_{TG} = r_{TG} + \text{TideCorr},
\]

where TideCorr is a tidal and datum correction (see \( d\phi\ dA \), Figure 2), computed using differences between \( r_{TG} \) and SSHMooring. This correction is dominated by an approximate 3° phase offset in the M2 constituent, with an amplitude of 0.089 m.

In summary, the calibration methodology presented here has two primary components. Firstly, during the formation flight period of the T/P and Jason-1 missions, the altimeter absolute bias is determined using comparison against the mooring sea surface height time series (SSHMooring). This time series has an absolute datum defined using the SSHBuoy data. Secondly, outside the formation flight period (i.e., both before and after the deployment of the mooring array), the cycle-by-cycle comparison with the altimeter is continued using the tide-gauge time series (SSH_{TG}), which has been corrected for geometrical and tidal differences using both the mooring and GPS buoy datasets.

**Instrumentation**

**Tide Gauge**

The Burnie tide gauge is located on the northern extremity of the Burnie wharf complex, fixed to the inshore side of a large concrete headwall extending into the Bay (Figure 3). The Bay forms an elongated bight in the coastline leaving the gauge exposed to Bass Strait, without significant influence from local harbor effects. A permanently operating GPS station (BUR1) is colocated with the tide gauge and serves as the primary reference station for this project. Data from the GPS unit are accessed remotely and archived by Geoscience Australia.

The gauge consists of an Aquatrak acoustic sensor and Sutron terminal unit. The gauge is one of 16 forming the Australian Baseline Sea Level Monitoring Project managed by the National Tidal Facility (NTF). Data are streamed from both the tide gauge and associated meteorological sensors to NTF and archived on a daily basis.

**GPS Buoys and Reference Network**

Two identical GPS buoys were deployed on an episodic basis at the offshore altimeter comparison point (Figure 4). The buoy design specifications and special operational considerations have been previously presented (Watson et al. 2003). The primary GPS reference station network consists of the permanently operating GPS station at the Burnie tide gauge, BUR1, and two additional sites TBCP and RKCP, operated on a episodic basis when deploying the GPS buoys (Figure 1). It is important to note a design specification within this study was to utilize identical receivers and choke ring antennas at all sites involved in the kinematic analysis of the GPS buoys. During the processing of the reference stations, data from BUR1, TBCP and RKCP are augmented with data from the Australian Regional GPS Network (ARGN) forming a 17-site regional solution (Twilley and Digney 2001).
Oceanographic Array

Three moorings were deployed along the T/P and Jason-1 ground track between the chosen altimeter comparison point and the Burnie tide gauge (Figure 1). The mooring array was deployed shortly after the Jason-1 launch in December 2001 and retrieved after the completion of the T/P and Jason-1 formation flight phase in September 2002. The instrument arrays at the inshore, center and offshore moorings were deployed at depths of 32 m, 47 m, and 51 m respectively (Figure 5).

The offshore mooring (40°45.2′S, 145°39.4′E) was positioned close to the altimeter comparison point and GPS buoy deployment site (within 1 km). Working from the base of the mooring upward, the instruments included:

- Applied Microsystems™ pressure gauge (depth 49.5 m),
- Seabird Microcat™ temperature and salinity recorder (depth 45 m),
- Steedman™ acoustic current meter (depth 36 m),
C. Watson et al.

FIGURE 5 Oceanographic Moorings in Bass Strait.

- Seabird Microcat™ temperature and salinity recorder (depth 26 m),
- Steedman™ acoustic current meter (depth 19 m),
- Seabird Microcat™ temperature, salinity and pressure recorder (depth 11 m).

The center mooring (40°54.0’S, 145°46.7’E) consisted of a RDI™ acoustic Doppler current profiler (ADCP) at a depth of 43 m. The inshore mooring (41°00.1’S, 145°52.0’E) consisted of a single Steedman™ acoustic current meter at a depth of 20 m.

This study draws primarily on data from the pressure gauge and the three Seabird Microcat™ instruments from the offshore mooring. Data from the other instruments is utilized for the determination of sea surface setup at the Burnie tide-gauge location.

Data Processing

Mooring Data

Data from the Applied Microsystems pressure gauge (Paroscientific Digiquartz sensor) and three Seabird Microcat instruments at the offshore mooring were used to derive a sea-surface height time series for the duration of the mooring deployment (dMooring). The pressure gauge was calibrated early in 2001, and is quoted as having an absolute accuracy of 15 mm, with repeatability at the ~5–6 mm level. A small calibration correction to account for the temperature dependence of the pressure sensor (computed by CSIRO) was applied to this time series. This correction was small with an amplitude of ~5 mm.

The dMooring time series was computed by first subtracting the local atmospheric pressure from the pressure gauge readings (half hourly samples) to give the pressure head of the water column. The atmospheric pressure time series (hourly samples) was obtained from the
Burnie tide-gauge site, some 40 km along track from the mooring location. To account for any potential differential atmospheric pressure between the two sites, model data from the Australian Bureau of Meteorology’s Limited Area Prediction System (LAPS) was utilized (Puri et al. 1998). Data for this study were extracted using the model with 5 km resolution. The differential pressure obtained from the model was applied as a correction to the Burnie pressure time series. This correction ranged between ±2 hPa and was indicative of the passage of pressure systems in the area in an eastward direction.

A time series of density profiles was calculated from the temperature and salinity data from the three Seabird Microcat instruments (5-minute sampling interval). The Seabird Microcat instruments were purchased new for this experiment, and the factory supplied calibrations were used. The temperature sensors are quoted as having an absolute accuracy of 0.002°C, and a stability of 0.0002°C per month or better. The salinity output is quoted as having an accuracy of 0.003 psu, and a stability of 0.003 psu per month. The two lower instruments showed clear evidence of fouling late in the deployment (31 March, 2002, following T/P cycle 351 and Jason-1 cycle 8). Salinity data for these two instruments were therefore replaced for this period by the salinity time series from the top instrument. The temperature data showed that the water column was well mixed for this fouling period.

Finally, the computed density profiles were used to convert the water-column pressures to depths on a 5-minute time base. We estimate the uncertainty associated with dMooring to be at the 12 mm level. This includes contributions from the pressure sensor (4 mm), estimation of the dynamic height (5 mm), and estimation of the overhead atmospheric pressure (10 mm). The resultant dMooring time series therefore provides a precise sea surface height time series relative to an arbitrary datum defined by the depth of the pressure sensor on the sea floor.

GPS Data

As stated previously, the absolute datum of the mooring time series is defined using data from the episodic GPS buoy deployments. The GPS data processing involves two distinct stages in order to derive SSH estimates for each GPS buoy deployment. Firstly, the reference station analysis computes the absolute position of each reference station in a terrestrial reference frame (ITRF2000, Altamimi et al. 2002) equivalent to the reference system used to define the orbits of both T/P and Jason-1. Secondly, the reference station positions are used to constrain the datum for the kinematic processing of each GPS buoy, producing raw 1 Hz SSH time series suitable for filtering and comparison to sea surface heights derived from the altimeters.

The reference station analysis (BUR1, TBCP and RKCP) remains mostly unchanged since the previous publication; see Watson et al. (2003) for the processing methodology. Since the recent Science Working Team (SWT) meeting in Arles, France (18–21 November 2003), GAMIT/GLOBK V10.1 was released (King and Bock 2003). In response to standardizing the solid earth tide code in Watson et al. (2003), the latest GAMIT release incorporates improvements in the application of the pole tide, standardizing the code with the IERS2000 formulation (McCarthy 2000). Specifically, previous versions used a different realization for the determination of the reference pole, hence offsetting the pole tide displacement when compared with the IERS2000 formulation. Differences in the pole tide displacement between the two models at the Bass Strait calibration site are at the 7 to 8 mm level. For the Bass Strait GPS network, the change in pole tide has lowered the absolute heights of BUR1, TBCP and RKCP by an equivalent magnitude (7 to 8 mm). This value varies at the 2 to 3 mm level depending on the strategy adopted for the reference frame realization process. This change has had a direct effect on our absolute bias estimates in
C. Watson et al.

comparison to those presented in Watson et al. (2003). This significant change demonstrates the meticulous (and continuous) approach required to standardize solutions, and compute accurate heights in an absolute reference frame.

The estimation of the formal error estimates associated with each coordinate component for each reference station remains problematic. Estimates of positional uncertainty from the GLOBK analysis (unscaled) are over optimistic, at the 2 mm level (1-sigma) in each coordinate component for the final determination of BUR1, TBCP and RKCP position. The difficulty in estimating a realistic uncertainty is three-fold. Firstly, residual seasonal effects in reference station time series invariably translate to an underestimation in the formal uncertainty of the station position and velocity (Dong et al. 2002; Mao et al. 1999, for example). Secondly, the uncertainty of site position and velocity is dependent on the noise model assumed in the time series. Assuming a white noise process in the presence of time-correlated noise processes will result in an underestimation of the uncertainty (Williams 2003). Finally, the reference station analysis for this study is also affected by utilizing a small number of episodic based GPS deployments. The short-term estimate of site position may therefore be contaminated by residual geophysical signals, measurement noise and model uncertainty (amongst others). These effects potentially offset the observed site position from the long-term mean position. The magnitude of this effect is dependent on the exact time of observation and the periodicity and magnitude of the residual geophysical signals (and other components) involved.

To assess the seasonal processes and systematic structure of the reference station network, a significantly long time series is required. For this analysis, the full time series at BUR1 and HOB2 (four years of common data) have been utilized. The long-term time series were computed by P. Morgan (School of Information Sciences and Engineering, University of Canberra), using the GAMIT/GLOBK software suite. HOB2 is located in Hobart on the southern Tasmanian coast, with a baseline separation from BUR1 of 232 km. Analysis of the full BUR1 and HOB2 time series (Figure 6a) shows significant correlation in the vertical component (0.82 using unsmoothed data and 0.85 using smoothed data). The weighted RMS variability (assuming a white noise process) of the BUR1 and HOB2 data are 10.2 mm and 11.2 mm, respectively (unsmoothed). This variability reduces almost by a factor of two to 6.7 mm for the residual (3.8 mm for the smoothed residual, Figure 6b). Common mode seasonal effects which may be contributing to this structure include contributions from residual geophysical loading signals, nontidal sea surface loading, groundwater and atmospheric loading to name a few.

Estimating the white noise and power law noise components of the BUR1 and HOB2 time series provides interesting results. Using the methodology described in Williams (2003), white noise estimates are 15.3 mm and 9.4 mm for BUR1 and HOB2, respectively. Power law noise estimates are significantly higher at 19.3 mm, and 22.9 mm respectively. While a complete treatment of these results is beyond the scope of this study, these results highlight the need to scale uncertainties determined for site position from the GLOBK analysis.

Given the high correlation of BUR1 and HOB2 over ~200 km, we assume the underlying signal at BUR1 (Figure 6a) would be largely reflected at the TBCP and RKCP sites. The BUR1 site therefore forms a proxy for our analysis of the TBCP and RKCP sites. In addition to considering the seasonal systematic structure of the time series, the short, episodic deployment of the TBCP and RKCP receivers must be considered. To assess this effect, the short-term position determined at BUR1 has been compared with the estimate computed from the full series (Figure 6c). Figure 6c shows six determinations of BUR1 position between 2001.7 and 2002.4 (same periods as for TBCP and RKCP). It is important to note these data do not lie at seasonal or daily extremes and are well distributed around
FIGURE 6 (a) Burnie (BUR1) and Hobart (HOB2) vertical GPS time series, (without error bars, arbitrary offset applied). Note the shaded section which encompasses the GPS buoy deployment window. The bold smoothed line on both time series shows a 30-day mean. (b) Residual BUR1-HOB2. (c) Absolute height for BUR1 long-term vs the episodic time series. Note the different units and time scale used. Values are shown with 1-sigma error bars.

the trend computed from the long-term series. The long-term trend passes well within the 1-sigma error estimates for each episodic position determination. Quantitatively, the short-term BUR1 position from our GLOBK analysis falls within 2 mm of the long-term estimate indicating the episodic deployments have satisfactorily sampled the underlying signal. Combining these analyses with recommendations presented in Williams (2003) and Mao et al. (1999), we choose a subjective scaling constant of 5 for our GLOBK positional uncertainties. This results in an uncertainty at the 10 mm level. We also maintain our previously adopted “fixed” error of 10 mm to recognize many of the systematic components of a GPS analysis strategy (for example, variability associated with observation weighting and
model selection, methods used to stabilize the reference frame realization and uncertainties associated with geocenter motion). This area of time-series analysis remains an area of further study.

The kinematic GPS analysis undertaken with the GPS buoy data remains unchanged from Watson et al. (2003). The solutions were however revisited to ensure the best possible results over the entire duration of the individual buoy deployment (up to four hours) as opposed to focusing on the period encapsulating the time of altimeter overflight. This provides a maximum number of $SSH_{Buoy}$ estimates to compute the datum of the $d_{Mooring}$ time series. Kinematic solutions have been computed for each buoy (Buoy 1 and Buoy 2) from each reference station (TBCP and RKCP), resulting in four solutions for each of the five deployments. Variability between solutions from different reference stations and between the two buoys provides an estimate of the precision obtained for a given deployment. A second indication of the GPS buoy solution variability is obtained by comparing $SSH_{Buoy}$ with the mooring time series ($d_{Mooring}$), when computing the mooring datum solution (Figure 7). The mooring datum solution (Equation 4) was undertaken using filtered 1 Hz $SSH_{Buoy}$ data. Both simple temporal mean and exponential filters were implemented, with negligible differences when using filter lengths between 20 and 30 minutes. When computing the mooring datum (i.e., the height of the mooring pressure-gauge zero on a nontidal, rigid crust, relative to the ellipsoid) the mean $SSH_{Buoy}$ time series from the four solutions for each deployment were utilized. Five “deployment mean” $SSH_{Buoy}$ time series were then combined to compute the “campaign mean” ($SSH_{Buoy} - d_{Mooring}$) used to define the mooring datum (Figure 7). The uncertainty placed on each estimate forming the “deployment mean” $SSH_{Buoy}$ time series is 15 mm. This estimate has been refined from Watson et al. (2003), to reflect changes in the methods used to combine data from two separate reference stations to the two buoys.

The difference between the $SSH_{Buoy}$ and $d_{Mooring}$ time series (Figure 7) yields valuable information on the quality of both the $SSH_{Buoy}$ and $d_{Mooring}$ time series. As the two sets of instruments were located in approximately the same location, the comparison is purely geometric, and no significant differential oceanographic signal is to be expected. It is anticipated the high frequency signal in the upper panels of Figure 7 largely reflects site specific and satellite constellation effects within the kinematic GPS solution. A much smaller contribution to this signal may also be related to the temporal smoothing (and hence inability to resolve high frequency events) on the mooring time series. Note solutions compared between buoys (B1 and B2 from the same reference station) show improved internal agreement when compared to individual buoy solutions computed from both reference stations (B1 from TBCP and RKCP, for example). This systematic pattern (Figure 7, lower panels) underscores the influence of local site-specific effects at each reference site (different sky obstructions, different multipath environment and different atmosphere).

The longer term signal apparent over the five deployments shown in the upper panel of Figure 7 is also of interest. Given the uncertainty of both the $d_{Mooring}$ and $SSH_{Buoy}$ time series, the signal is not considered significant. The presence of a seasonal signal in the $SSH_{Buoy} - d_{Mooring}$ series is unlikely, as both instruments were collocated. Settlement of the mooring array is considered possible, however cannot be substantiated with these data.

The final campaign mean (i.e., mean($SSH_{Buoy} - d_{Mooring}$)) is used to define the mooring datum, and is applied to the mooring time series to derive $SSH_{Mooring}$. The absolute datum of the mooring time series is therefore completely dependent on the value of mean($SSH_{Buoy} - d_{Mooring}$). With the constrained datum, the $SSH_{Mooring}$ time series is directly comparable to the two altimeters over the duration of its deployment.
FIGURE 7 Mooring datum determination. The upper panel shows the difference between the GPS Buoy solution and the surface height determined from the mooring data for the five available buoy deployments. The thick bar indicates the mooring datum estimated from the times series. The lower panels show the SSH\textsubscript{Buoy} departure from the mean SSH\textsubscript{Buoy} for each deployment. The observed variability of the final mooring datum estimate (±1 standard deviation of SSH\textsubscript{Buoy} – d\textsubscript{Mooring}) is indicated by the shaded region in the upper panels. The arrows marked with “OF” indicate the time of satellite overflight with the T/P and J-1 cycle number labeled on either side of the arrow.
**Tide Gauge Data**

The tide gauge data are utilized to extend cycle-by-cycle comparisons with both the T/P and Jason-1 altimeters. As mentioned previously, to correct (or transform) the tide gauge time series ($r_{TG}$) out to the comparison point ($SSHTG$), corrections are required taking into account tidal differences (both in amplitude and phase), geophysical differences (tidal and nontidal loading) and geometric differences (geoid slope and datum differences).

Taking advantage of the SSH$_{Mooring}$ time series, the difference in sea surface height ($SSH_{Diff}$) was computed using concurrent data from the tide gauge recorded over the duration of the mooring deployment (Equation 6).

$$SSH_{Diff} = SSH_{Mooring} - r_{TG}.$$  

The $SSH_{Diff}$ time series has a standard deviation of 0.069 m, with the series dominated by tidal frequencies in the semidiurnal band and higher. A small component of these harmonics will be differential tidal loadings (predominantly differential ocean loading). A standard harmonic tidal analysis was undertaken on the $SSH_{Diff}$ time series, solving for tidal frequencies of diurnal frequency and higher. The time series is dominated by a $\sim$3 degree phase difference in the M2 constituent, with an amplitude of 0.089 m. Using the results from the tidal analysis, both hindcast and forecast predictions enable the generation of a predicted difference ($SSH_{PredictedDiff}$) in sea surface height between the Burnie tide gauge and the comparison point. These data are used to compute a corrected tide-gauge SSH time series for all time periods containing valid Burnie tide-gauge data (Equation 7).

$$SSH_{TG} = r_{TG} + SSH_{PredictedDiff}.$$  

Note that the datum for $SSH_{TG}$ is directly defined by the GPS buoy and mooring time series (as $SSH_{Mooring}$ was utilized when forming $SSH_{Diff}$ in Equation 6). This methodology therefore precludes the necessity to estimate a marine geoid and reduces the solution to a geometrical framework, defined by the GPS buoys.

To estimate the nontidal contribution to the differences observed between the comparison point and Burnie tide gauge locations, along-shore, low-frequency currents and cross-shore winds were investigated. To first order, the along-shore current will be balanced by an on/offshore geostrophic pressure gradient (Equation 8), given as:

$$fu = -g \frac{\partial h}{\partial y},$$

where $f$ is the coriolis parameter, $u$ is the along-shore current (low passed), $g$ is the acceleration due to gravity, $\partial h$ is the change in SSH, and $\partial y$ is the offshore distance ($\sim$18 km). The low-passed currents (using a cutoff period of two days) from the shallow current meters from the inshore and offshore moorings were combined to derive a mean current time series. The current data from the center mooring (the ADCP) had a number of gaps and also finished earlier than the data from the other moorings, so was not used. A time series of the sea surface setup was computed using the mean-current data and the relation provided in Equation 8. During the deployment presented here this correction had a magnitude of a few centimeters (standard deviation 8 mm), with a small annual signal.

An additional nontidal difference investigated between the two locations is wind-induced sea surface setup. An on/offshore wind stress could be balanced by an on/offshore
pressure gradient as indicated in Equation 9, as:

$$\frac{\tau_y}{\rho h} = g \frac{\partial h}{\partial y}, \quad (9)$$

where $\tau_y$ is the on-shore wind stress, $\rho$ is the water density, $h$ is the water depth, $\partial h$ is the change in SSH, and $\partial y$ is the offshore distance ($\sim 18$ km). Wind data from the meteorological instruments associated with the Burnie tide gauge were used for this analysis. The effect is an order of magnitude smaller than the setup from the alongshore current, but has been included in the final setup time series. For the period of current meter deployment, the corrected tide gauge SSH time series was then defined as (Equation 10)

$$\text{SSH}_{\text{TG}} = r_{\text{TG}} + \text{SSH}_{\text{PredictedDiff}} + \text{SSH}_{\text{Setup}}. \quad (10)$$

Analysis of the difference between the low passed $\text{SSH}_{\text{TG}}$ and $\text{SSH}_{\text{Mooring}}$ time series (Figure 8) shows the precision obtainable using this methodology. The difference time series (Figure 8, panel C) has a range of 6.7 cm, and standard deviation of 1.3 cm. A range of signals with various frequencies and magnitudes at the 1–2 cm level are apparent in this difference time series. Contributions to these signals could include a range of error sources both at the tide gauge and mooring sites. Components are likely to include errors in the atmospheric pressure time series (at both locations), insufficient modeling of sea surface set-up induced by both wind and current variability, residual differential tidal and nontidal deformation of the crust, errors in the computation of the dynamic height at the mooring location, consolidation of the mooring anchor into the sediment, and errors in the temperature calibration of the tide gauge. At this stage, it is not possible to separate and quantify the error components between the two sites. Further correction to one or both of these time series is under investigation.

**TOPEX/Poseidon Altimeter Data**

The data processing methodology for T/P has been modified slightly from the process used in Watson et al. (2003). The analysis is based on the 1 Hz TOPEX data from the most recent MGDR-B data files (see Benada 1997).

The NASA POE orbits on the MGDR-Bs were used, and the following corrections from the MGDR-B were applied:

- center-of-gravity,
- dry troposphere,
- TMR wet troposphere correction (see notes below),
- seastate bias (Gaspar 4 parameter),
- ionosphere (mean of all reasonable values between 39°48′ S and 40°48′ S. Using other smoothers (e.g., as recommended in GDR manuals) makes negligible difference).

Two problems with data from the TOPEX Microwave Radiometer (TMR) are well documented in the literature. The first of these is a drift in the 18 GHz brightness temperature channel, which translates into a drift in the measured atmospheric water vapor, and hence leads to an error in the wet troposphere (TMR) correction to the altimeter range. A correction for this effect has been available in the “GCP” product provided by JPL PO.DAAC (http://podaac.jpl.nasa.gov/products/product170.html). Instead of using the GCP correction, our methodology has been to recalculate the 18 GHz brightness temperatures,
FIGURE 8  Low passed sea surface heights and currents at the Burnie and offshore comparison point locations. Panel A is the Burnie tide gauge series with tidal and set-up corrections applied. Panel B is the offshore mooring series, Panel C (note the different scale) is the difference (tide gauge—mooring) and Panel D is the along- and cross-shore currents.

(Ruf 2000, 2002) and compute the wet troposphere correction from the brightness temperatures (Keihm et al. 1995). These two approaches are equivalent. However, our methodology simplifies the correction process for the T/P dataset required for this study. This approach increases the magnitude of the MGDR-B wet troposphere correction by approximately 6–7 mm for the formation flight period (equivalent to raising the measured altimeter SSH by approximately 6–7 mm).

The second correction required for the TMR data is the effect of the satellite yaw-steering mode, which is related to component heating (Brown et al. 2002), 2.4 mm in sinusoidal yaw and −1.4 mm for fixed yaw. The 15-hour thermal settling time has not been taken into consideration, as it does not affect pass 088 for the cycles used in this study (all yaw state transitions are more than 15 hours away). The correction for yaw state was not applied in Watson et al. (2003).
FIGURE 9 Typical TMR wet delay profiles across Bass Strait (north to south from left to right), showing the original MGDR-B TMR wet delay, the Ruf (2002) and Brown et al. (2002) corrected TMR and the extrapolated TMR correction.

Brightness temperature data from the radiometer shows clear signs of contamination when the nadir point is \(\sim 40-50\) km from the nearest land (Rocky Cape, Figure 1). This contamination is evident when inspecting the time series of brightness temperatures (and hence wet troposphere corrections) as the satellite travels on its descending pass over Bass Strait. Typical examples from three T/P cycles (Figure 9) show the contamination as the satellite reaches a latitude of approximately \(40.45^\circ\)S (approximately 40 km from land).

The comparison point for this study is inshore from the point where this contamination becomes evident. To overcome the land contamination, two methodologies have been investigated. Firstly, a mean value is computed within the latitude band \(39.9^\circ\)S and \(40.45^\circ\)S and used at the comparison point. Secondly, a linear regression is computed using values in the same latitude band, and extrapolated south to the comparison point (Figure 9). Given the subtle yet systematic trend in the wet troposphere correction for most passes across Bass Strait, the linear extrapolation methodology appears most appropriate. Both methodologies have been compared against the wet troposphere time series computed at the Burnie GPS station (wet path delays from the altimeters, i.e., the absolute value of the GDR correction have been used in this analysis). The wet troposphere delay at the Burnie GPS was computed using the GPS total zenith delays from the GAMIT analysis (King and Bock 2003) and local temperature and atmospheric pressure observations taken from the Burnie site using the methodology presented in Bevis et al. (1992). GPS data were available for comparison against 81 cycles between T/P cycles 232 and 365.

The land affected MGDR-B TMR wet delay (correcting using the Ruf (2000), Brown et al. (2002) formulations) is biased high against the GPS derived value (mean 11.2 mm, standard deviation 13.0 mm), as shown in Figure 10. Using the mean delay in the specified latitude range results in an offset of \(-3.8\) mm and a standard deviation of \(13.9\) mm when compared to the GPS data. The extrapolated value does slightly better compared with the GPS data: mean \(-1.7\) mm and standard deviation \(11.7\) mm (Figure 10). Based on these results, the extrapolated value of the corrected TMR data was adopted and used to compute the \(\text{SSH}_{\text{Altimeter}}\) for GDR data points either side of the comparison point.

Corrections for the solid earth tide, pole tide, and ocean loading were applied to the 1 Hz sea-surface height measurements, which were linearly interpolated to the point of
FIGURE 10  TMR vs BUR1 GPS wet delay. Both the MGDR-B TMR wet delay (corrected using the Ruf (2002), Brown et al. (2002) corrections) and the extrapolated TMR wet delays are shown compared with the wet delay extracted from the BUR1 GPS solution.

closest approach (PCA) to the comparison point. Negligible difference was found between using linear and cubic spline interpolation strategies.

A cross-track geoid gradient was finally applied to compute SSH Altimeter at the comparison point. The gradient applied accounts for the across track separation between the altimeter PCA and comparison point (typically ±500 m). The gradient applied is 10 ± 3 mm/km (see Watson et al. 2003).

Jason-1 Altimeter Data

The Jason-1 bias computations presented here are based on the GDR data files (see Picot et al. 2001). The POE orbits on the GDRs were used, and the following corrections from the GDR were applied:

- dry troposphere,
- JMR wet troposphere correction (see notes below),
- seastate bias,
- ionosphere (using the same smoothing process as applied for T/P).

As expected, the JMR wet troposphere correction shows similar land contamination effects when compared to the TMR correction (Figure 10). Once again, a linear extrapolation of values between latitudes 39.9°S and 40.45°S was adopted, and applied to compute 1 Hz SSH data either side of the comparison point.

A clear bias is present between the TMR and JMR data during the formation flight period of the mission (Figure 11). The bias (JMR wet delay–TMR wet delay) at the Bass
FIGURE 11 Residual altimeter wet delay, JMR–TMR.

Strait comparison point is −9 mm indicating that the JMR instrument is measuring drier when compared with TMR. Given the strong agreement between the BUR1 GPS and the TMR data, the JMR difference suggests it is a contributing factor to the observed J-1 SSH bias.

As for T/P, corrections for the solid earth tide, pole tide, and ocean loading were applied to the Jason-1 1 Hz sea surface height measurements, which were linearly interpolated to the point of closest approach. Finally, the cross-track geoid gradient was applied to derive the $\text{SSH}_{\text{Altimeter}}$ at the comparison point.

Error Budget

An error budget has been compiled for the Bass Strait calibration site in order to assess the formal uncertainty of the final absolute bias estimates for T/P and Jason-1. As in Watson et al. (2003), the error estimates have been divided into fixed (systematic) and variable (quasi-random) terms (Table 1). The error budget is complicated by the addition of the systematic terms, especially in relation to the GPS analysis.

In computing the error terms for the mooring datum solution, we assume the measurements can be considered independent every 30 minutes. The sample size used in deriving the variable error component is therefore 26. Estimates for the uncertainty associated with the mooring SSH have been derived from manufacturer’s specifications. Estimates for T/P SSH (35 mm) have been adopted from Chelton et al. (2001). For Jason-1 SSH, we adopt 30 mm based on corrected 1 Hz GDR SSH with SWH less than 1.5 m (Vincent et al. 2003).

Final uncertainties for absolute bias have been computed for the formation flight period where 18 overflights were used to compute bias estimates. The systematic terms have been summed in quadrature with the quasi-random terms (making the assumption of independent estimates). The minimum uncertainty obtainable using this technique (with unlimited overflights) is therefore at the 10 mm level. The final uncertainty for the absolute bias calculation computed over the formation flight period is 14 mm for T/P and 13 mm for Jason-1.

Outside the formation flight period, the error budget must consider the increased error associated with the corrected tide gauge sea surface heights (not indicated in Table 1). Analysis of atmospheric pressure differences, and computed sea-surface setup over the formation flight period indicate an additional 10 to 15 mm of variable error per overflight comparison. This additional error term is minimized by the significant increase in overflight comparisons possible using the longer tide-gauge time series, leading to an uncertainty at the 12 to 13 mm level for 60 cycles of data.
TABLE 1 Error Budget for the Bass Strait Calibration Site During the Formation Flight Period of the Mission

<table>
<thead>
<tr>
<th>Error budget: Formation flight period</th>
<th>Fixed</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS Buoy SSH (SSH_{Buoy})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Reference station solution</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>- Kinematic solution</td>
<td>—</td>
<td>15</td>
</tr>
<tr>
<td>- Antenna height and PCV</td>
<td>3</td>
<td>—</td>
</tr>
<tr>
<td>- Cross-track geoid gradient</td>
<td>—</td>
<td>3</td>
</tr>
<tr>
<td>(a) SSH_{Buoy} Total:</td>
<td>10 mm</td>
<td>18 mm</td>
</tr>
</tbody>
</table>

| Mooring depth (d_{Mooring})          |       |          |
| - Pressure gauge                     | —     | 4        |
| - Dynamic height                     | —     | 5        |
| - Atmospheric pressure               | —     | 10       |
| (b) d_{Mooring} Total:               | 0 mm  | 12 mm    |

| Mooring datum (SSH_{Mooring})        |       |          |
| - SSH_{Buoy} (from (a) above)        | 10    | 18       |
| - d_{Mooring} (from (b) above)       | —     | 12       |
| Datum SSH_{Mooring} total: (*)       | 10 mm | 4 mm     |

| Altimeter SSH (SSH_{Alt})            |       |          |
| - J-1 SSH_{Alt} total: (**)          | —     | 30 mm    |
| - T/P SSH_{Alt} total: (**)          | —     | 35 mm    |

| Grand totals (absolute bias uncertainty) |       |          |
| = sqrt(Datum SSH_{Mooring}^2 (fixed) + Datum SSH_{Mooring}^2 (variable) + (sqrt(SSH_{Alt}^2 + d_{Mooring}^2)/sqrt (n))^2) | 13 mm | 14 mm |

| J-1 Bias: (**)                        |       |          |
| T/P Bias: (**)                        | 13 mm | 14 mm    |

| e.g., J-1 = sqrt[10^2 + 4^2 + (sqrt(30^2 + 12^2)/sqrt (18))^2] |       |          |

*The SSH_{Mooring} error estimate assumes independent GPS buoy comparisons on a half hourly basis, therefore n = 26 over 5 buoy deployments.
**Uncertainties are per overlight, based on SWH < 1.5 m.
***n = 18 over the formation flight period.

Absolute Bias Results

The principal absolute bias results for this publication are centered on the formation flight period of the T/P and Jason-1 missions, using SSH_{Mooring} as the in situ reference. Secondary results are included for Jason-1 (cycles 1–60), T/P Side A (cycles 1–235) and T/P Side B (cycles 236–365). Each of these secondary results have been computed using the SSH_{TG} time series as the reference.

Results for the formation flight period (Figure 12), show a mean T/P bias of 0 mm with a standard error about the sample mean of 3.5 mm. Results from Jason-1 appear more variable, with a mean bias of +152 mm (std. err. 7.7 mm). Computing a relative bias between Jason-1 and T/P using only common cycles, the relative bias at Bass Strait is +150 mm (std. err. 6.3 mm). The absolute bias variable error as computed in the error budget (8 mm for T/P and 9 mm for Jason-1) is in accord with, although slightly larger than, the observed variability (3.5 mm for T/P and 7.7 mm for Jason-1).
To highlight the strength of the methodology, bias estimates have been computed over the same period utilizing the secondary in situ reference time series, SSH$_{TG}$. These estimates are $+4$ mm (std. err. $4.7$ mm) for T/P and $+160$ mm (std. err. $7.6$ mm) for Jason-1. Given the significantly higher error estimates for the SSH$_{TG}$ time series and the small number of comparisons over the formation flight period ($n = 18$), these estimates must be considered equivalent (c.f. $0$ mm and $+152$ mm, respectively). Extending the Jason-1 analysis to include cycles 1–60 reduces the mean bias slightly to $+148$ mm (std. err. $6.2$ mm), as shown in Figure 13.

At the time of writing the bias at the NASA Harvest site for Jason-1 (GDR POE Orbit) was $+138 \pm 17$ mm (Haines et al. 2003). The bias from the Corsica site is slightly lower at $+120 \pm 7$ mm (Bonnefond et al. 2003). Note the uncertainties placed on the Harvest bias estimate have been computed from a rigorous error budget (similar to that used here). The uncertainties placed on the Corsica estimate are however a measure of variability and reflect the standard error about the sample mean. The true uncertainty of the Corsica estimate is therefore expected to be slightly larger.

Geographically correlated errors (specifically related to the orbit computation) are expected to contribute to these differences. For comparison, the altimeter processing strategy was altered to utilize the JPL GPS reduced dynamic orbit, integrated with the GRACE GGM01S gravity model (Haines et al. 2004). The Jason-1 mean absolute bias at Bass Strait with the GPS orbit reduces significantly by $17$ mm to $+131$ mm (std. err. $5.9$ mm) for
cycles 1 to 60. The same strategy at the Harvest site results in a less significant reduction in the bias estimate by approximately 5 mm (Haines et al. 2003). Taking the orbit differences into account, bias estimates at Bass Strait and Harvest show exceptional agreement (131 and 133 mm). Bias estimates from Corsica do not show any significant dependence on the orbit strategy (over the full time series), and hence remain somewhat low in comparison to the Harvest and Bass Strait estimates. The systematic difference between orbit solutions can be attributed primarily to differences between the JGM-3 and GRACE gravity models. Differences between these models show distinct geographically correlated patterns, including significant differences over the Australian region. The differences also reflect variations in the long wavelength components, indicative of the improvements made with the GGM01S model (Bonnefond et al. 2003). A recommendation to come out of the SWT meeting in Arles, was to switch to the GRACE gravity field for future GDR data production.

In addition to orbit differences, regional errors in the observed troposphere path delay may be a contributing factor to differences in bias estimates. Slight variations in computational standards may also contribute to these small differences. For example, the difference observed when standardizing the pole tide algorithm for this study demonstrates the importance of correctly standardizing measurement models, especially given absolute heights are required in this field.

During the T/P mission, two different altimeters have been used in operation onboard the spacecraft (designated Sides A and B). The Side B altimeter was put into operation following degradation of the Side A unit during February 1999. The last full cycle to utilize data from the Side A instrument was cycle 235. Utilizing the corrected tide gauge sea surface heights, absolute bias estimates for T/P Sides A and B can be computed (Figure 14). Over this period the mean absolute bias (Side A) is +6 mm (std. err. 2.3 mm). Recent investigations by Chambers et al. (2003), revealed a potential problem with the sea state bias (SSB) model used in conjunction with the Side B data delivered as part of the MGDR-B product. The impact of the new SSB model derived by Chambers et al. (2003) was investigated as part of this study. As expected, the new SSB model makes insignificant difference for the Side A, changing the mean bias to +7 mm (std. err. 2.3 mm). Results from the Side B instrument on T/P are also presented in Figure 14. The Side B absolute bias estimate using the MGDR-B SSB correction is +3 mm (std. err. 2.8 mm). The estimate with the Chambers SSB correction is marginally increased to +7 mm (std. err. 2.7 mm).

FIGURE 13 Jason-1 absolute bias for POE and GPS reduced dynamic orbits using cycles 1–60.

Conclusions

The use of GPS buoys combined with an oceanographic mooring array at the Bass Strait calibration site provides a unique calibration methodology for the determination of absolute altimeter bias. The calibration site is also unique as the sole absolute verification site located in the southern hemisphere, and unlike the sites at Harvest and Corsica, it utilizes altimeter data from a descending pass. Over the formation flight period of the two missions, our mean absolute bias is 0 ± 14 mm for T/P and +152 ± 13 mm for Jason-1. Using only common cycles, our relative bias for this period is +150 ± 11 mm. The uncertainty tolerances placed on these estimates is considered realistic given the error terms involved. The limiting error sources are the systematic error term associated with the GPS reference station analysis, followed by the uncertainty associated with the altimeter SSH estimates.

Excluding the systematic error terms from the error budget results in a reduction of our formal uncertainties to the 8 to 9 mm level over the formation flight period. This reduction is considered unrealistic for a rigorous absolute bias uncertainty. The separation of the fixed and quasi-random error components does however provide an indication of the expected variability in a relative sense. Analysis of the observed variability of the bias estimates (Figure 12) shows comparable estimates to theoretical values derived in the error budget (Table 1).

The significant bias (order 150 mm) present in the Jason-1 data remains unexplained. Differences observed between the JMR, TMR, and GPS wet delay estimates indicate the JMR may be a small contributor to the bias (below the 10 mm level). Bias results over the duration of the Jason-1 mission (cycles 1–60), also highlight significant differences depending on the choice of orbit (+148 mm for the GDR POE orbit and +131 mm for the JPL GPS reduced dynamic orbit). This difference is attributed principally to differences in the underlying gravity fields associated with each orbit computation strategy (JGM-3 for the GDR POE and GGM01S for the JPL GPS). These distinct geographically correlated orbit differences over the Australian region (amongst others) emphasizes the need for continued analysis, especially considering the evolution in obtainable precision over recent years. The geographically correlated orbit errors also highlight the benefit of a well-distributed set of calibration sites to quantify observed differences in an absolute sense. We consider this a primary advantage of in situ calibration sites.

After considering geographical differences associated with orbit computation, bias estimates from Harvest and Bass Strait agree to well within estimated uncertainty tolerances. Bias estimates from the Corsica site remain slightly lower, yet still within the formal
uncertainties. Careful calibration of ongoing altimeter missions is therefore essential for continued sea level studies, particularly those involving the computation of regional to global mean sea level, and associated trends (Church et al. 2001).

References


